Metal-Matrix Composites for Liquid Rocket Engines

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This article presents an overview of current research and material requirements for metal-matrix composite (MMC) technologies being developed for liquid rocket engines (LRE). Developments in LRE technology for the U.S. Air Force are being tracked and planned through the integrated high payoff rocket propulsion technologies program (IHPRPT). Current efforts and research requirements for three types of MMC systems are discussed: aluminum-, copper-, and nickel-matrix material systems. Potential applications include turbopump housings, rotating machinery, and high-stiffness flanges and ductwork.

INTRODUCTION

Liquid rocket engines are just beginning to capitalize on improvements in materials and process technologies that have made significant impacts on the performance of aircraft and stationary power-generating turbines. Turbine inlet temperatures of jet aircraft engines have increased by more than 160% since 1955.[1] Of that increase, 120°C resulted from improved temperature capability of jet engine turbine blade materials. Formerly composed of polycrystalline alloys, those blade materials are made of directionally solidified single crystals. Performance has also been improved by an initiative by the electrical-power industry, through a DOE consortium, to develop ceramic materials that will reduce emissions, increase efficiency, and reduce maintenance load. By the end of 1999, SiC/SiC combustor liners with environmental barrier coatings had survived 8,000 hours of field testing, cutting NO_x emissions by 40% and CO emissions by 80%.[2] Similar system-level performance improvements are being sought by the rocket propulsion industry through the application of new materials and processing technologies.

The integrated high payoff rocket propulsion technology program (IHPRPT) has established performance improvement goals for rocket propulsion through 2010. IHPRPT is a joint effort of the U.S. Department of Defense, NASA, and industry, managed by the Air Force Research Laboratory and divided into three phases of improvement demonstration. All advancements in liquid rocket engines can be measured by improved thrust-to-weight [or increased specific impulse (thrust) achieved divided by weight flow rate of propellant consumed], increased reliability, and decreased cost. In the past, these areas have been inextricably connected in that advancing one area has typically involved compromises in the other two areas. For example, improved performance is possible, but only with a concomitant increase in cost and decrease in reliability. Of course, an optimum advancement would allow a simultaneous increase in performance, reliability, and a decrease in cost. The IHPRPT program is an attempt to achieve such simultaneous and optimum advancements.

IHPRPT phase II goals are to be demonstrated through engine-level tests in 2005. Some of the goals to be demonstrated are a thrust-to-weight increase of 60%, cost reduction of 25%, and a mean time between replacement (MTBR) of 60 missions. These overall goals are broken down into component-level objectives for weight reduction and increased performance. Approaches to meet objectives combine evolutionary engineering improvements, engineering design changes, and advanced materials insertion. In 1997, the materials working group was established by the IHPRPT to help guide the insertion of new materials technologies into rocket propulsion. Materials technologies can enable new engine technologies and influence evolutionary design improvements including reducing the weight of ducting, bellows, and flanges, improving the performance of cryogenic fuel pumps, and decreasing the weight of nozzle and exit cone structures. Two new concepts need materials and process technologies advancements to be implemented before they can be fully developed: the full-flow engine cycle and transpiration cooling. Both have existed as design concepts for years, but these engineering technologies require high-temperature, oxidation-resistant materials and finely controlled porous materials, respectively, to enable their demonstration.

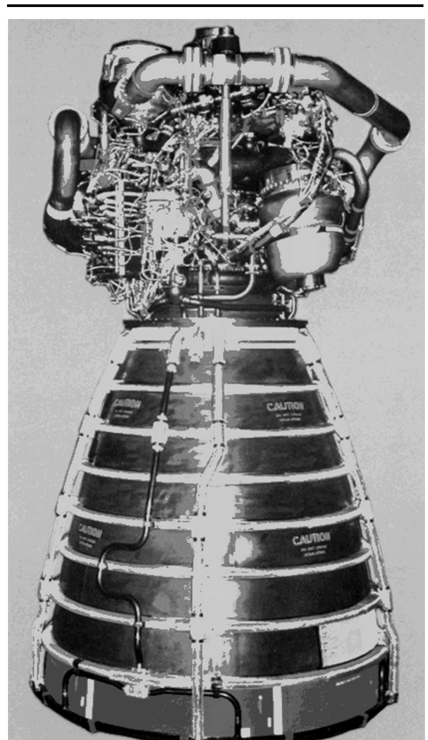

Figure 1: Space shuttle main engine.

LIQUID ROCKET ENGINE OVERVIEW

The purpose of the liquid rocket engine (LRE) is to accelerate a mass to overcome gravity or change orbital velocities.[3] LREs generate acceleration by converting the chemical energy from fuel and oxidizer in the propellants to kinetic energy of mass flow through the nozzle. On the space shuttle main engine (SSME), illustrated in Figure 1, the energy conversion process involves pumping large volumetric flow rates of cryogenic propellants (443 kg/s) of LOx and 74 kg/s of LH_2 to extremely high pressures (48 MPa), and combusting the propellants to transform their chemical energy into thermal energy at a temperature of 3,300°C.[4] The combustion products are then accelerated through a converging-diverging nozzle to transform their thermal energy into orderly kinetic energy, exiting the nozzle at very high velocities to produce thrust (2 MN).

The example of the space shuttle main engine illustrates the two major taxonomies in the rocket engine for which IHPRPT is tracking performance improvements: propellant-management devices (PMDs) and combustion- and energy-conversion devices (C&ECD). PMDs include the propellant pumps, the turbines that drive them, and ducting. C&ECD hardware includes the pro-

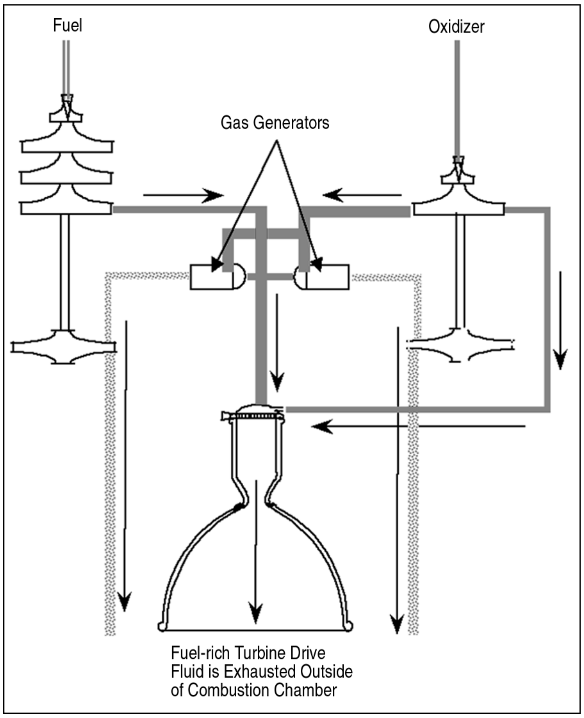

Figure 2: Power cycle flow schematic of the gas generator cycle. (Combustion chamber cooling not shown.)

pellant injection system, main combustion chamber, nozzle, exit cone, and other combustion devices such as the preburners and gas generators necessary to drive the turbines.

The specific components, arrangement of components, and environments endured by those components depend on the power cycle of the engine. The power cycle of the engine is named for both the flow path the propellants follow and the disposition of the propellants downstream of the power turbines. There are two general classes of rocket power cycles: open and closed.[5] In an open cycle, the spent turbine gases are exhausted either directly overboard or downstream of the nozzle throat. Such a disposal method allows a greater pressure drop across the turbine, but the rocket engine suffers a performance loss because this mass of turbopump drive propellants is not accelerated to the same velocity as the rest of the propellant exhausted through the main combustion chamber. The highest practical turbine inlet temperature must be attained to reduce the performance losses as much as possible. This temperature is always limited by the capability of the turbine materials. The huge F-1 and cryogenic J-2 rocket engines used on the Saturn-5 launch vehicle are examples of an open cycle called the gas-generator cycle. Figure 2 is a flow schematic illustrating a gas-generator cycle in which the turbine drive energy is produced by combusting a small quantity of propellants exclusively used to power the turbopump.

The closed cycle is so called because all the rocket propellants are exhausted through the main combustion chamber. There are several methods for adding energy to the turbine drive fluid while still combusting all of the propellants, including the staged-combustion cycle and the expander cycle. The SSME is an example of the staged-combustion cycle engine, which uses a hydrogen-rich steam as the turbine-drive fluid. Figure 3 illustrates a flow schematic for a staged-combustion cycle: a portion of the fuel and oxidizer is partially combusted in a small preburner, then the turbine-exhaust fluid is sent to the combustion chamber with the rest of the propellants and all propellants achieve the maximum nozzle-exhaust velocity. The second type of closed cycle is the expander cycle, which uses forced convective cooling of the combustion chamber with one of the propellants to provide a high-energy turbine-drive fluid. While most rocket engines employ regenerative combustion-chamber cooling, only the expander cycle uses this heat-exchanging technique to provide turbine-drive energy without additional combusting devices. Because no additional combustion is employed, expander-cycle engines have the lowest turbine-inlet temperatures. Figure 4 illustrates a flow schematic for an expander-cycle engine.

Variants of the aforementioned engine cycles also exist. One variant, an engineering design change currently under development, is the full-flow staged-combustion cycle. In the full-flow engine cycle, the fuel turbopump is driven with a fuel-rich steam and the oxygen turbopump is driven with an oxidizer-rich steam. (Refer to Figure 5 for a flow schematic for a full-flow staged combustion cycle engine.) In contrast, the staged-combustion cycle used on the SSME drives both the fuel and oxidizer turbopumps with hydrogen-rich steam. Operation in this oxidizer-rich environment is difficult because ignition and sustained combustion are likely if materials are not properly selected. Nonetheless, some materials have been identified that perform suitably in this oxidizer-rich environment for ducting, turbines, and turbine housings. Development of materials with higher specific strengths and higher temperature capability suitable for application in this environment would enable both weight reductions and performance gains in full-flow cycle engines.

In current design practices, the rocket industry prefers to use deterministic design methodologies and ad hoc failure criteria, even for critical components. As with other industries, fracture mechanics and probabilistic structural design methodologies are applied only in specialized circumstances. While high- and low-cycle fatigue have often been considered as design drivers for turbine components, time-dependent failure modes such as thermal-cycle induced creep and environmental cracking are relatively new to rockets, with the advent of reusable rocket engines like the SSME. For that reason, the rocket industry tends to select materials for use in a specific application based on the results of specific tests. The uniaxial tensile tests result in not only yield and ultimate strength information, but also a strain-to-yield, or strain-to-failure, value, which is referred to as ductility. Ductilities greater than 6% are desired for the strength-of-materials design approach to result in a conservative structural design. Ductilities as low as 3% are acceptable in particular cases. Because of the extreme environments to which rocket components are subjected, material selection is frequently based on properties other than strength or ductility. Oxygen compatibility, hydrogen embrittlement resistance, fatigue strength, joinability, or high thermal con-

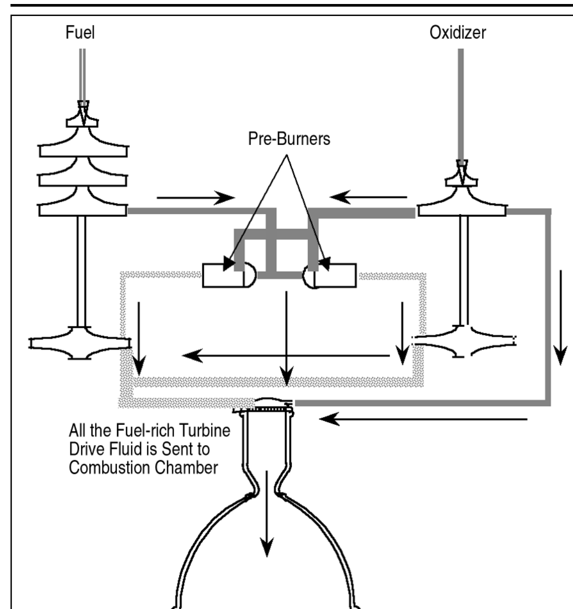

Figure 3: Power cycle flow schematic of the staged combustion cycle. (Combustion chamber cooling not shown.)

ductivity are some of the other driving parameters for material selection for specific components.

ALUMINUM METAL-MATRIX COMPOSITES

The rocket industry is turning to aluminum MMCs primarily to reduce the weight of structural components.[6] The potential uses for aluminum MMCs, which are numerous throughout the engine, fall into three general categories: stiffness-driven components, warm-temperature applications, and cryogenic applications. Stiffness-driven components include flanges, thrust chamber jackets, and support structures. These components transfer loads from one structure to another through both bonded and bolted joints. While not in direct contact with either hot combustion products or cryogenic propellants, these components tend to operate in moderate thermal and chemical environments. Current systems use nickel-based superalloys in these applications for both high stiffness and compatibility with mating surfaces. The parameters for materials in these applications are high stiffness (moduli greater than 220 GPa are desired), ability to be welded or brazed, physical compatibility with dissimilar materials, and ability to bear strength in bolted joints. Near-net-shape processing techniques that are capable of fabricating generally axisymmetric shapes with multiple radii of curvature are necessary. Ceramic particulate and discontinuous fiber-reinforced aluminum MMCs are being developed. Secondary thermal processes, such as brazing and welding are commonly used during subassembly fabrication and must be developed considering MMC capabilities. MMCs with inserts and mixed reinforcement types (particulate, chopped fiber, and continuous fiber) are desired for these applications to functionally grade a welded interface to a stiff bolted joint. Methods of joining MMCs and dissimilar materials also require development.

Warm-temperature applications for aluminum MMCs are considered high-temperature applications for aluminum, but moderate-temperature environments in rocket engines. Turbine rotating components, stationary elements, and housings in expander cycle engines run at temperatures up to 260°C. Warm propellant ducting and backup structures also operate in this thermal environment, but at lower stress levels. Rotating machinery has the most severe requirements in this area, with the material strength necessary for single-stage pump designs pushing 862 MPa. These components are exposed to (usually) hydrogen-rich turbine drive gases and require both creep and fatigue resistance. Nickel-based superalloys are currently used for these components. Although an alternative to expensive machining of forged billets for these components is desired, complex shapes with good surface finishes are needed.

Complex shapes with smooth interior surfaces are also needed for cryogenic pump components. Housings, inducers, impellers, and stationary guide vanes must operate at the –244°C temperature of liquid hydrogen. Meticulous design practices are employed to account for varying shrinkage between components during cool down to maintain tight tolerances and carefully engineered flow paths. Hydrogen compatibility is required along with fatigue resistance. Currently, forged and machined titanium alloys are used for these components because of their good properties at low temperatures. To improve on the performance of the titanium alloys, strengths in the range of 675 MPa, ductilities greater than 6%, and fatigue limits greater than 275 MPa at temperature with densities less than 4 g/cm^3 are desired. Low, or controllable, CTEs would allow greater design flexibility. As with other components, near net-shape processing techniques are desired to alleviate the reliance on expensive forging and machining processes.

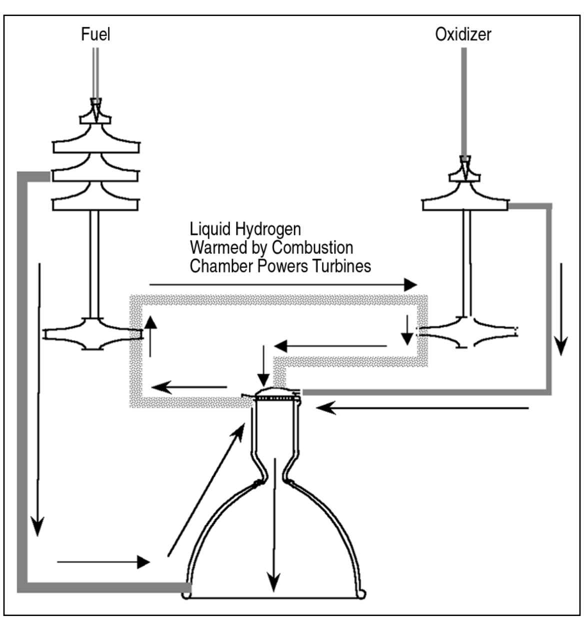

Figure 4: Power cycle flow schematic of the expander cycle. (Note lack of gas generators or preburners.)

Recent efforts by the rocket industry to develop aluminum materials for component applications have centered on manufacturing nanophase monolithic aluminum alloys. At this time, a nanophase alloy composition has not been optimized; however, an aluminum-magnesium alloy that maintains a grain size on the order of 10 nm has been developed. Still being developed are processes ranging from efficiency of powder attrition to large-mechanical-work-input fabrication techniques.

Current aluminum MMC material and process development efforts are exploring a number of materials and approaches for achieving IHPRPT objectives.[6] Near-net shape casting techniques are being pursued to provide a cost-effective approach for producing the complex-shaped components required for turbopump components. Key technologies to be addressed include controlling the volume fraction and distribution of reinforcing particles in the preform. (See article in this month's issue by Joseph M. Kunze and Clifford C. Bampton.) Control of particulate volume fraction and distribution are required to control the coefficient of thermal expansion, stiffness, strength, and ductility of the MMC. Selective reinforcements, both discontinuous and continuous, may offer important approaches for tailoring the properties of the material to the local stresses while reducing the cost of the reinforcement. In addition, selective reinforcements provide an approach for producing functionally graded properties. Issues associated with joining, manufacturing, and design must also be addressed in these efforts. Both particulate and chopped-fiber reinforced aluminum MMCs are currently being investigated and strengths as high as 620 MPa have been achieved in particulate-reinforced systems.

COPPER METAL-MATRIX COMPOSITES

The applications for copper MMCs in rocket engines are more limited than for aluminum MMCs. The two properties of copper that make it attractive as a matrix material for rocket-engine components are its oxygen compatibility and high thermal conductivity. Oxygen compatibility is essential for oxidizer PMDs in the full-flow engine cycle, in which the oxygen turbopump housing and ducts will be in direct contact with high-temperature oxygen-rich steam. These applications also require strength at temperature and creep resistance. To be considered for use in an oxygen-rich environment, a material must not support combustion at 69 MPa oxygen, and cannot be susceptible to ignition by impact of a 1.5 mm diameter aluminum particulate in a supersonic stream of oxygen.[7] Operating conditions can be varied to account for material capabilities, but strengths of 413 MPa are required at 260°C with densities less than 7.5 g/cm^3

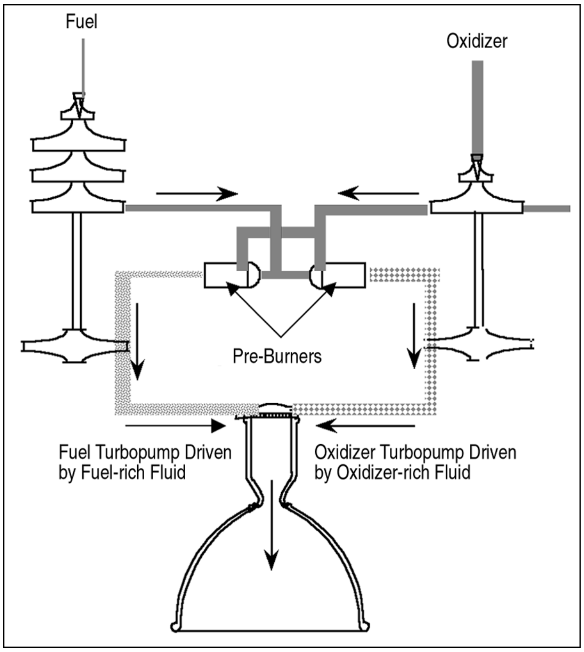

Figure 5: Power cycle flow schematic of the full-flow staged combustion engine cycle. (Combustion chamber cooling not shown.)

for some applications. As with aluminum MMCs, near-net shape processing techniques that create good surface finishes with little machining must be developed for copper MMCs.

Heat-conduction applications are primarily thrust-chamber liners, cooled either regeneratively or through transpiration. While most regenerative cooling schemes require the high conductivity of monolithic copper, increased strength, creep, and fatigue resistance are needed to overcome deformation due to thermal cycling stresses. The thrust-chamber liner is exposed to the 20 MPa combustion gases on the inner surface and cryogenic propellants on the outer surface, where it mates with the structural jacket. Although the material requirements depend on the thrust-chamber design, the high heat-transfer rates required to cool the combustion-chamber liner have precluded use of copper-matrix composites in the past.

Previous copper MMC material development efforts attempted to fabricate continuous graphite fiber-reinforced copper composites for heat-transfer applications. Fiber wetting, tow infiltration, and subsequent delamination problems could not be overcome at that time and more recent activities have utilized alumina tows for reinforcement. While the same general approaches and issues relate to both aluminum and copper MMCs, the higher melting temperature of the copper offers an additional challenge, along with controlling the interfacial bond. It is hoped that many of the design methodologies developed for aluminum MMCs will transfer to copper MMC technologies with only minor adjustments.

NICKEL METAL-MATRIX COMPOSITES AND OTHER MATERIALS

The primary driver for nickel-based MMCs in LREs is the full-flow cycle engine. Turbine components require high strength, creep and fatigue resistance at temperature, oxygen compatibility, and corrosion resistance. Nickel-based superalloys are the materials of choice for these components in systems currently under development. While increased strength, stiffness, and creep resistance may be achieved by creating composites with SiC particles or fibers, oxygen compatibility cannot be compromised for components in the oxygen-rich drive gas environment of the full-flow cycle engine. To be considered for use in an oxygen-rich environment, a material must not support combustion at 69 MPa oxygen and can not be susceptible to ignition by impact of a 1.5 mm aluminum particulate in a supersonic oxygen stream.[7] Thermal-shock environments during the engine-start transients preclude the use of coated material systems for turbine-blade applications at this time. Therefore, the entire bulk of a turbine-blade material must be resistant to the oxygen-rich combustion product environment. Because turbine blades and disks are typically uncooled for their roughly nine-minute operational cycle, short operational periods where bulk material temperatures reach 730°C are not uncommon. Strengths greater than 1040 MPa at temperature are desirable with material densities less than 6.5 g/m^3 for some designs. These stress, temperature, and chemical environments are severe, and increasing MTBR goals make these material property goals even more strenuous to achieve.

Other non-rotating components must also survive extreme operating environments. Injector faceplates and bodies, along with preburners, must be resistant to oxidation, corrosion, and hydrogen embrittlement at high temperatures. Injectors meter and direct the flow of propellants into the main combustion chamber. Preburners are the small combustion chambers in which the turbine drive gas is generated. Current systems, some of which are actively cooled, use cobalt alloys for these components. Extreme thermal environments (gas temperatures approaching 918°C) and pressures up to 62 MPa are projected for these components in future engines. Monolithic silicon nitride is being applied to the injector body, but the difficulty of mating the ceramic body to a metallic thrust chamber has not been overcome to permit testing of this ceramic injector. Because of the generally axisymmetric shape of the injector body, continuous-fiber composites have been suggested for this application, however, component mating requirements create challenges for continuous-fiber composites.

Currently funded efforts are working to improve the oxygen compatibility and strength of monolithic nickel-based superalloys and an improved stressed-oxidation response has been demonstrated. Nickel MMCs show great promise for application to rocket components, but the materials, process, and design technologies are considered to be too immature for component demonstration at this time. Material and process development efforts in this area are being planned for funding within two to three years.

WHERE ARE WE HEADED?

MMCs are expected to provide important materials solutions for the next generation of rocket component needs.[6] On the current IHPRPT roadmaps, components employing MMCs should be demonstrated in 2005 with additional advances continuing through 2010. Further into the future, weight and turbine inlet temperature goals may favor more aggressive development of ceramics and ceramic-matrix composites for liquid rocket engines. Thermal and environmental coatings technologies will also require development. Polymer-matrix composites are currently being studied for application to moderate temperature and chemical environment components. However, ductility requirements, geometric constraints, and environment compatibility needs in liquid rocket engines ensure that metal-matrix composites will play an important role in rocket technology for the foreseeable future.

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